

Single-Proton Removal Reaction Study of ^{16}B

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Abstract

The low-lying level structure of the unbound system ^{16}B has been investigated via single-proton removal from a 35 MeV/nucleon ^{17}C beam. The coincident detection of the beam velocity ^{15}B fragment and neutron allowed the relative energy of the in-flight decay of ^{16}B to be reconstructed. The resulting spectrum exhibited a narrow peak some 85 keV above threshold. It is argued that this feature corresponds to a very narrow ($\Gamma \ll 100$ keV) resonance, or an unresolved multiplet, with a dominant $\pi(p_{3/2})^{-1} \otimes \nu(d_{5/2}^3)_{J=3/2+} + \pi(p_{3/2})^{-1} \otimes \nu(d_{5/2}^2, s_{1/2})_{J=3/2+}$ configuration which decays by d -wave neutron emission.

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Amongst the light exotic nuclei, the two-neutron halo systems are arguably the most intriguing. Apart from the halo character, these nuclei exhibit the so-called “Borromean” property whereby, in a three-body description, none of the constituent two-body subsystems — n - n and core- n — are bound [1]. Modelling such systems thus requires knowledge of the core- n interaction. Given that measurements of neutron scattering on the core nucleus are in practice impossible [32], the interaction must be derived from the structure of the corresponding unbound nucleus — ^{10}Li , for example, in the case of ^{11}Li [2].

Currently the heaviest established two-neutron halo system is ^{17}B [4]. Analyses of both the ^{15}B fragment momentum distribution following the breakup of a ^{17}B beam [5] and the total reaction cross section on a carbon target [4] indicate that the halo neutrons wavefunction contains roughly equal admixtures of $\nu 1d_{5/2}^2$ and $\nu 2s_{1/2}^2$ configurations. The recent observation of the gamma-ray de-excitation of the two bound excited states of ^{15}B [30] in the dissociation of ^{17}B suggests that core excitations may also play a role [7, 8].

Very little, however, is known about ^{16}B . Its unbound nature was most recently confirmed by Kryger *et al.* in an investigation of the reaction products from the breakup of ^{17}C where an upper limit on the lifetime of some 191 ps was derived [9]. Evidence for a very low-lying state, some 40 keV above the ^{15}B - n threshold, together with indications for a higher lying level 2.40 MeV above threshold was found in a heavy-ion multi-nucleon transfer reaction study [10]. Whilst benefiting from the advantages of the high intensities of stable beams, such reactions suffer from very low yields (cross sections of order $\mu\text{b/sr}$ and thin targets — $\sim 1\text{ mg/cm}^2$), a complex reaction mechanism and hence selectivity, often coupled with significant backgrounds as illustrated by Ref. [10].

As originally demonstrated by the investigation of ^{10}Li by Zinser *et al.* [11], the few-nucleon breakup of high-energy radioactive beams can be employed to populate, and study through the fragment-neutron final-state interaction (FSI), unbound nuclei. In addition to benefiting from high cross sections (typically 10-100’s mb), the high energies result in the strong forward focussing of the reaction products (increasing the effective detection acceptances) and permit the use of very thick targets (~ 100 ’s mg/cm^2). Consequently measurements with beam intensities as low as ~ 100 pps are feasible. Importantly, as discussed by Zinser *et al.* within the context of the sudden approximation, the stripping at high energy of one or more protons (for example) will not perturb the configuration of the neutrons. As such the choice of a projectile with a well known structure should permit the structure of

the final-states of the unbound system to be inferred. Indeed, the use of a ^{11}Be beam with a predominately $\nu s_{1/2}$ configuration allowed the threshold s -wave structure of ^{10}Li to be probed [11, 12]. More recently, two-proton removal from ^{11}Be has been employed to explore the structure of ^9He [12].

In this spirit we report here on an investigation of the low-lying level structure of ^{16}B using single-proton removal from a high-energy beam of ^{17}C . As discussed below, the shell structure of ^{17}C has been established by a number of recent experiments [13, 14, 15, 16, 17].

The ^{17}C beam of mean energy 35 MeV/nucleon was produced via the reaction on a Be target of a 63 MeV/nucleon ^{18}O primary beam supplied by the GANIL cyclotron facility. The beam velocity reaction products were analysed and purified using the LISE3 fragment separator [18]. The resulting secondary beam composition was 98% ^{17}C with an average beam intensity of ~ 7000 pps. A time-of-flight measurement performed using the beam tracking detectors (see below) and a parallel-plate avalanche counter (PPAC) located some 24 m upstream of the secondary reaction target allowed the ^{17}C ions to be separated in the offline analysis from the remaining contaminants. The energy spread of the ^{17}C beam, as defined by the settings of the LISE spectrometer, was 2.5% ($\Delta E/E$). The effect on the relative energy between the fragment and neutron from the in-flight decay of an unbound system, such as ^{16}B , is negligible compared to the overall resolution (see below) and no event-by-event correction based on the measured beam energies was required.

The secondary beam was delivered using the separator onto a 95 mg/cm^2 ^{nat}C target. Owing to the relatively poor optical qualities of the secondary beam (beam spot size ~ 10 mm diameter), two position-sensitive PPAC's located just upstream of the secondary reaction target and separated by 60 cm were used for tracking. The impact point of the beam on target was thus reconstructed event-by-event with a resolution of ~ 1.5 mm (FWHM). The charged fragments from the reactions were detected and identified using a Si-Si-CsI telescope centred at 0° and located 11.3 cm downstream of the target. The two $500 \mu\text{m}$ thick silicon detectors, each comprising 16 resistive strips, were mounted such that the strips of the first detector provided for a measurement of position in the horizontal direction whilst those of the second detector the vertical position. The impact point along each strip was determined with a resolution of 1 mm (FWHM). In addition to the energy-loss measurements provided by the silicon detectors, the residual energy of each fragment was determined from the signals derived from the $5 \times 5 \text{ cm}^2$, 2.5 cm thick CsI crystal. The measurement of the total energy

deposited in the telescope was calibrated using a “cocktail” beam, which included ^{15}B , and for which the energy spread was 0.05%. Runs were made over a range of rigidity settings of the LISE spectrometer such that the ^{15}B calibration points covered the range of energies expected from the in-flight decay of ^{16}B . The total energy resolution of the telescope was determined to be 1.2% (FWHM). In addition to the measurements of breakup on the C target, data was also acquired with the target removed so as to ascertain the contribution arising from reactions in the telescope. As the reaction of interest – $\text{C}(^{17}\text{C}, ^{15}\text{B}+n)\text{X}$ – is a charge changing one, this contribution was found to be negligible as expected [19].

The neutrons were detected using 97 liquid scintillator elements of the DEMON array [20]. The modules, each of which has an intrinsic detection efficiency of $\sim 35\%$ at 35 MeV, were arranged in a staggered two-wall type configuration covering polar angles up to 39° in the laboratory frame [21]. This arrangement provided for a reasonable detection efficiency for the $^{15}\text{B}-n$ reaction out to ~ 5 MeV relative energy, whilst retaining a good energy resolution (see below). The neutron energy was derived from the time of flight measured between the PPAC located closest to the target and DEMON. The final energy resolution was 5% (FWHM). The neutron energy spectrum exhibited, in addition to the beam velocity neutrons produced in the projectile breakup, a low-energy component arising from neutrons evaporated from the target. Such events were removed in the off-line analysis by imposing a low-energy threshold of 13 MeV [21].

Turning to the results, the most easily extracted observable is the single-neutron angular distribution in coincidence with the ^{15}B fragments. As may be seen in Figure 1, the angular distribution is very forward focussed ($\theta_{1/2} \approx 2^\circ$), indicating that the in-flight decay is dominated by events with low relative energies. The angle integrated cross section is 6.0 ± 1.5 mb, in good agreement with the value of 4.4 ± 0.3 mb obtained by Krieger *et al.* at a somewhat higher beam energy (52 MeV/nucleon) for the inclusive channel $\text{C}(^{17}\text{C}, ^{15}\text{B})\text{X}$ [9].

The reconstructed $^{15}\text{B}-n$ relative-energy spectrum is displayed in Figure 2. As expected, significant strength resides close to the decay threshold, in particular in the form of a very narrow structure (FWHM ≈ 100 keV) at ~ 100 keV. It should be pointed out that the measured relative energy may be directly identified with the energy in ^{16}B provided that the ^{15}B fragment is in the ground state. As noted earlier, ^{15}B was recently found to possess two bound excited states ($E_x=1.33$ and 2.73 MeV) [30]. Given the relatively limited yield (655 events) in the $\text{C}(^{17}\text{C}, ^{15}\text{B}+n)\text{X}$ channel (Figure 2), a triple coincidence measurement

including gamma-ray detection was precluded. Structural considerations (see below) coupled to the relative high-energies of the bound excited states in ^{15}B , lead to the conclusion, however, that the feature observed does not arise from the decay of a high-lying level in ^{16}B to a bound excited state in ^{15}B .

Before proceeding any further in the interpretation, the effects of the experimental setup must be examined. The experimental response functions were generated using a GEANT [22] based simulation code [23, 24]. The predicted efficiency for detecting a $^{15}\text{B}-n$ pair is shown in Figure 3. Importantly, the response is a smooth function of relative energy exhibiting no features which could mimic a sharp resonance-like state. The gradual fall off from a maximum of some 7% at around 1.5 MeV is in line with simple geometrical considerations based on the angular coverage of the neutron array (the efficiency for the detection of the ^{15}B fragments is essentially 100%). The resolution (FWHM) in the reconstructed relative energy, which is dominated by the finite angular size of the individual DEMON modules, was determined to vary as $0.320 \cdot \sqrt{E_{rel}}$ (MeV), with a resolution of 100 keV at 100 keV decay energy. This suggests that the width of the feature observed in the decay spectrum (Figure 2) is dominated by the experimental resolution. As a check on the simulations, comparison was made between the ^7He decay spectrum – the ground state resonance of which is well established – reconstructed from data acquired in the $\text{C}(^{14}\text{B}, ^6\text{He}+n)\text{X}$ reaction at 41 MeV/nucleon and that predicted by the Monte Carlo calculations. As discussed elsewhere the agreement was very good [21, 25]. Cross-talk events, whereby scattering resulted in two detectors firing, were discarded by analysing only single-neutron events. The probability of cross-talk occurring was well reproduced by the simulations. Finally, we note that rate of events for which a neutron was first scattered without detection by a module (or non-active element in the setup) and then detected in another module was predicted to be less than $\sim 5\%$ of the total number of events and did not introduce noticeable distortions in the reconstructed relative energy spectrum.

In addition to the sharp resonance-like peak, the reconstructed $^{15}\text{B}-n$ relative-energy spectrum exhibits a very broad underlying distribution which slowly decays in intensity with increasing energy (Figure 2). This distribution is interpreted as arising from the population of the non-resonant continuum – that is $^{15}\text{B}-n$ events for which no significant FSI occurs [33]. Such uncorrelated events may be generated from the experimentally measured $^{15}\text{B}-n$ pairs via event mixing. In order to avoid the effects of possible residual correlations [26] an

iterative technique was applied [27]. The distribution so generated and normalised to the data at high relative energy is shown in Figure 2 (dashed line). The agreement is very good and reinforces the notion that the resonance-like peak is not an artifact of the experimental setup [34].

In order to interpret the data, the formalism developed in Refs [11, 12] has been followed. Briefly, within the sudden approximation, the lineshape of the relative energy distribution is derived from the overlap of the initial bound-state wave function, describing the relative motion between the valence neutron and core of the projectile, and the unbound final-state wave function describing the fragment-neutron interaction. Here the wave functions were obtained using standard Woods-Saxon potentials ($r_0=1.25$ fm, $a_\nu=0.6$ fm) adjusted to reproduce the neutron separation energy for the initial state and the resonance energy for the final state. As described in Ref. [21], for a narrow resonance ($\ell_n > 0$) this approach results in a lineshape identical to a Breit-Wigner distribution incorporating the appropriate ℓ_n -dependent penetrability.

As noted in the introduction, high-energy single-proton removal should, within the context of the sudden approximation, leave the neutron configuration of the projectile unperturbed. Here then, the low-lying states populated in ^{16}B should resemble a $\pi p_{3/2}$ hole coupled to the ^{17}C ground state neutron configuration. Shell model calculations indicate that the latter is dominated ($\sim 65\%$) by approximately equal admixtures of $\nu(d_{5/2})_{J=3/2+}^3$ and $\nu(d_{5/2}^2 s_{1/2})_{J=3/2+}$ [14], as confirmed by recent measurements of neutron removal from ^{17}C [13, 14, 16]. As such a $0^- - 3^-$ multiplet of states may be expected to be preferentially populated in ^{16}B .

Calculations carried out within the $p - sd$ model space using the WBP interaction [28] predict that such a low-lying multiplet is indeed present in ^{16}B (Figure 4 and Table I). The states which are expected to be populated may be identified by the spectroscopic factors for single-proton removal from the $\pi p_{3/2}$ orbital. As listed in Table I, the first four levels predicted to be strongly populated are the lowest lying $0^- - 3^-$ states. Energetically the first three members of this multiplet can only decay to the ^{15}B ground state. Of the other states calculated to be relatively strongly populated, only the 3_2^- which is predicted to lie at 2.736 MeV could, in principle, produce a narrow low-lying line in the relative energy spectrum, such as that observed here, via d -wave neutron decay to the second bound excited state of ^{15}B (2.73 MeV, $7/2^-$). However, only a small fraction of the decay is predicted to

proceed in such a manner ($b_d = 0.04$). As such, it is reasonable to conclude that the peak observed in the ^{15}B - n relative-energy spectrum arises from one, or a combination, of the 0_1^- , 3_1^- and 2_1^- states.

The spectroscopic factors for the neutron decay to the ^{15}B ground state are listed in Table I. All the states predicted to be strongly populated are expected to decay essentially exclusively by d -wave neutron emission. The single-particle width for d -wave decay from a resonance at 100 keV is only 0.5 keV. Clearly then, the experimental resolution will dominate the lineshape of the low-lying states in the relative energy spectrum. Assuming such a single, isolated low-lying resonance, described by an $\ell=2$ Breit-Wigner lineshape modulated by the experimental response function, and the uncorrelated ^{15}B - n distribution described earlier, it was found that the reconstructed relative energy spectrum could be very well reproduced for a resonance energy $E_r=85\pm 15$ keV (Figure 2). Interestingly, this energy is compatible with that for the lowest-lying feature observed in the multi-nucleon transfer reaction study of Kalpakchieva et al. [10] (Figure 4).

Simulations undertaken assuming the population of the 0_1^- , 3_1^- and 2_1^- levels according to the predicted energies and spectroscopic factors (Table I), indicate that the 0_1^- ground state would be observed as a narrow peak at threshold well separated from a higher lying and somewhat broader but more intense peak arising from the unresolved 3_1^- and 2_1^- levels [21]. As displayed in Figure 5, if the separation between the 0_1^- , 3_1^- and 2_1^- levels is reduced to some 150 keV, rather than the predicted 950 keV, and the relative strengths remain as predicted, the simulated distribution matches the measured decay-energy spectrum. It has been noted previously that the shell model overestimates the excitation energies of bound states in this mass region [30], although to a much lesser degree than may be occurring here. This was attributed to the weak binding of the valence neutrons. It is conceivable, therefore, that such an effect could be amplified in the case of an unbound system such as ^{16}B .

As to the higher-lying states predicted to be populated ($E_{rel} > 2$ MeV), the degradation in the resolution with increasing relative energy ($\text{FWHM} > 0.45$ MeV) makes their observation challenging. Indeed, the most easily observable of these – the 1_1^- calculated to lie some 2 MeV above the ground state – would, assuming the predicted strength and no feeding to the first excited state of ^{15}B , be at the limits of detection given the present statistics.

In summary, the low-lying level structure of the unbound nucleus ^{16}B has been investigated via single-proton removal from a ^{17}C beam. The reconstructed ^{15}B - n relative energy

spectrum exhibited a narrow resonance-like structure near threshold. Simple considerations and comparison with shell-model calculations suggest that this peak arises from a very narrow ($\Gamma \ll 100$ keV) resonance, or an unresolved multiplet ($0_1^-, 3_1^-, 2_1^-$), with a dominant $\pi(p_{3/2})^{-1} \otimes \nu(d_{5/2}^3)_{J=3/2^+} + \pi(p_{3/2})^{-1} \otimes \nu(d_{5/2}^2, s_{1/2})_{J=3/2^+}$ configuration which decays by d -wave neutron emission.

Future measurements, with significantly improved resolution and higher statistics might locate the high-lying states and, moreover, attempt to resolve the possible multiplet of near threshold states – the latter being of some importance in the context of the shell model predictions. Whilst technically very challenging, the detection of gamma-rays in coincidence with the $^{15}\text{B}-n$ fragments should be included to remove any possible ambiguity regarding the excitation energies of the levels in ^{16}B . Finally, it is interesting to note that the preliminary analysis of a measurement undertaken at RIKEN of neutron removal from ^{17}B finds a $^{15}\text{B}-n$ relative energy spectrum almost identical to that reported here [31].

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- [34] The uncorrelated distribution so generated includes the effects of the experimental response function.

J^π	E_x (MeV)	C^2S	b_d	b_s
0^-	0.0	0.27	0.08	
3^-	0.649	1.10	0.37	
2^-	0.943	0.32	0.65	0.01
4^-	1.389			
2^-	1.748	0.02	0.07	0.53
1^-	1.988	0.48	0.50	
1^-	2.504			
3^-	2.736	0.45	0.28	
3^-	3.226	0.01	0.03	
5^-	3.508			
4^-	3.689			
2^-	3.782	0.13	0.21	0.03
4^-	3.958			

TABLE I: Levels below 4.00 MeV in ^{16}B predicted by $(0+1)\hbar\omega$ shell model calculations using the WBP interaction [28] in the $p - sd$ valence space. E_x is the excitation energy with respect to the 0^- ground state, which is calculated to lie 0.164 MeV above the $^{15}\text{B}-n$ threshold [28] ($E_x = E_r + 0.164 \text{ MeV}$); C^2S is the spectroscopic factor for removing a $0p_{3/2}$ proton from ^{17}C ; and b_d and b_s are the spectroscopic factors for d and s -wave neutron decay to the ^{15}B ground state (these are only listed for states with non-zero C^2S).

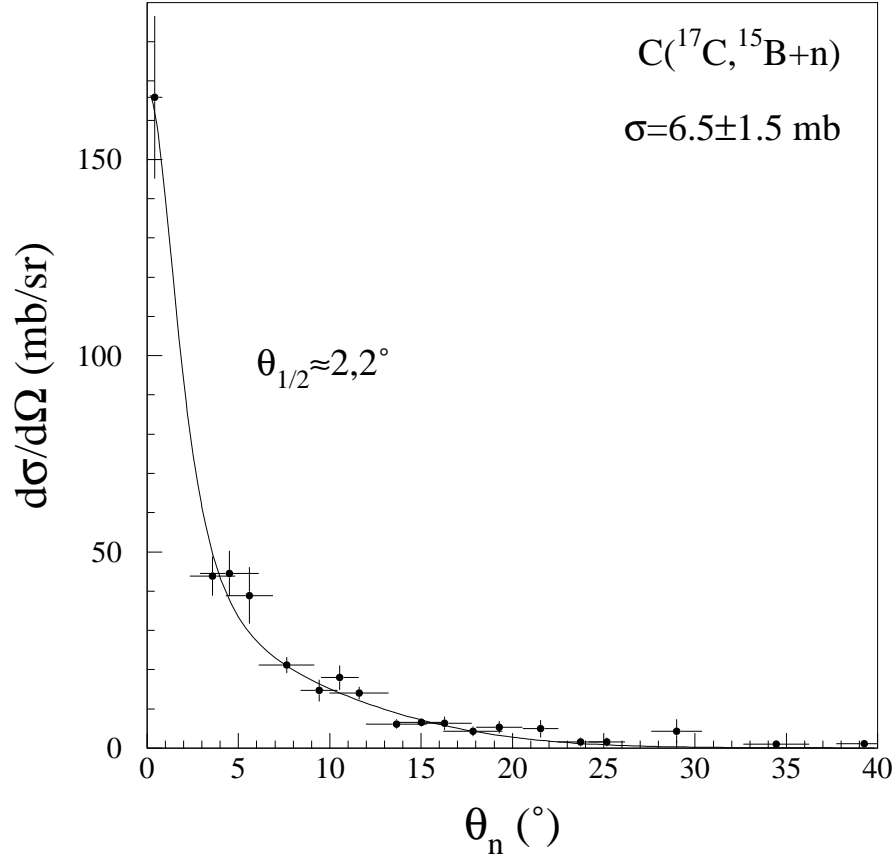


FIG. 1: Single-neutron angular distribution for the reaction $C(^{17}\text{C}, ^{15}\text{B}+n)X$ at 35 MeV/nucleon. The solid line is an adjustment to the data using a Lorentzian plus Gaussian lineshape.

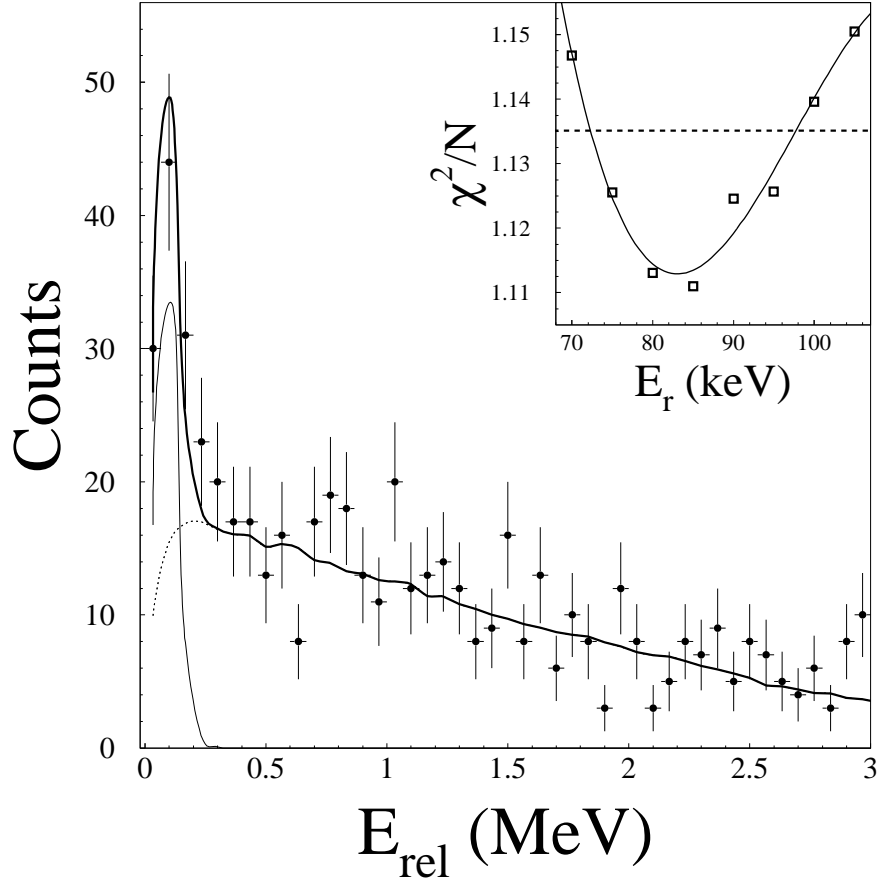


FIG. 2: Reconstructed $^{15}\text{B}-n$ relative energy spectrum. The thick solid line corresponds to the best adjustment to the data for a very narrow d -wave resonance ($E_r=85\pm 15$ keV, $\Gamma = 0.5$ keV) folded with the simulated experimental response function (thin solid line) plus a broad uncorrelated distribution obtained by event-mixing (dotted line) – see text. The insert shows the reduced χ^2 as a function of E_r , where the horizontal line deliniates χ^2+1 .

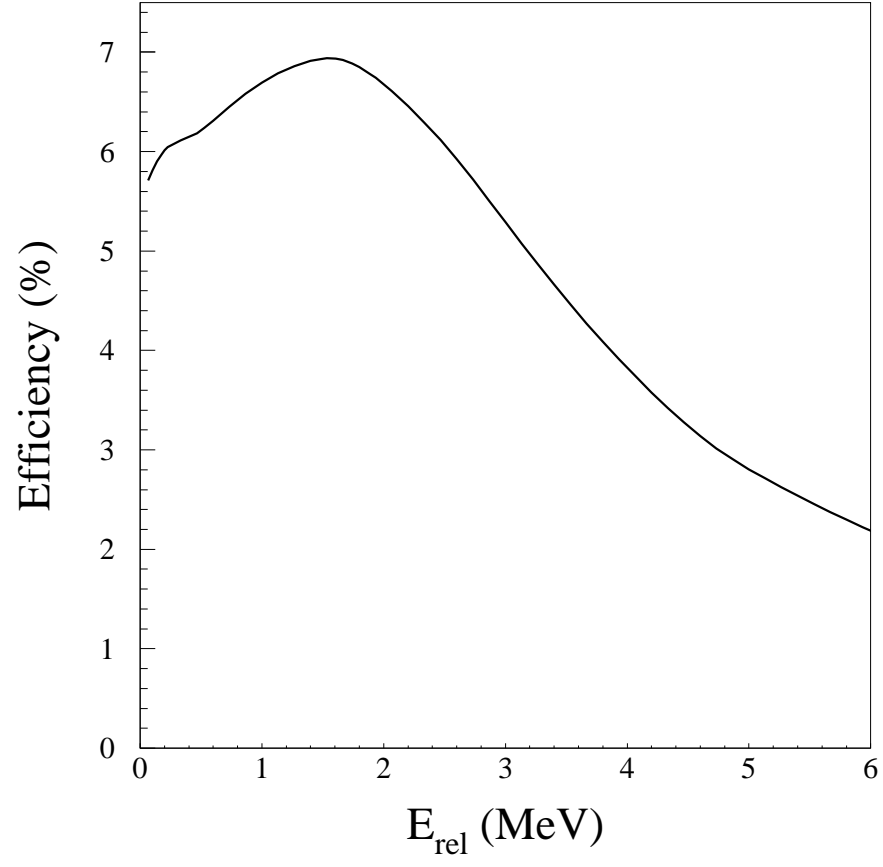


FIG. 3: Simulated detection efficiency for the ^{15}B - n pair as a function of relative energy (see text for details).

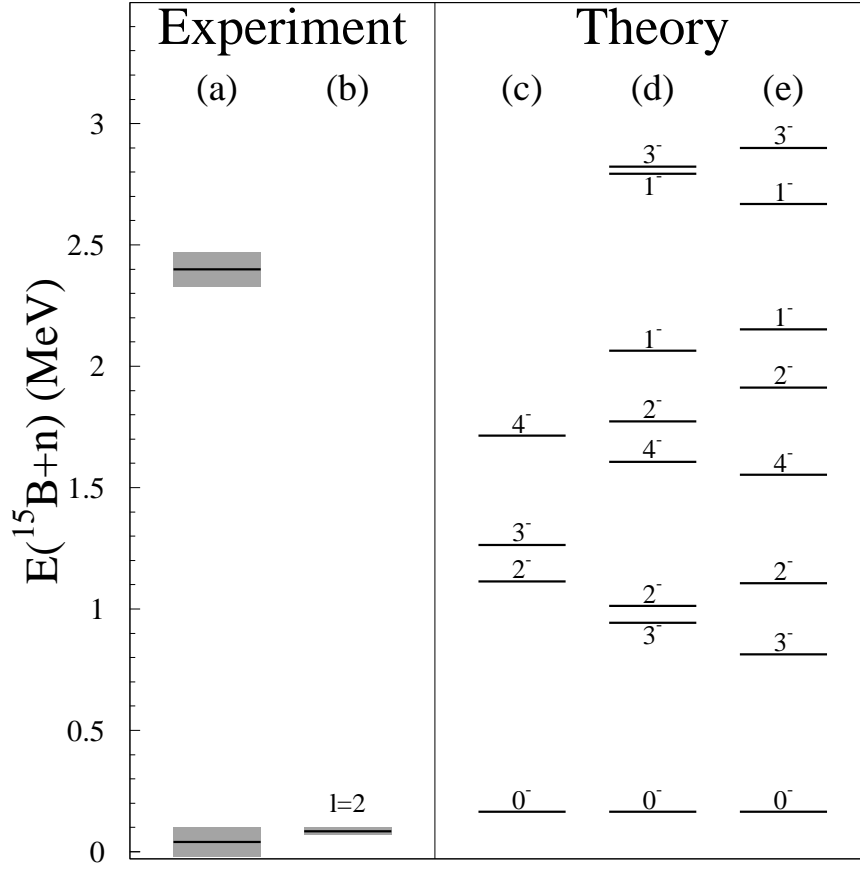


FIG. 4: Compilation of energy levels in ^{16}B measured in (a) the $^{14}\text{C}(^{14}\text{C}, ^{12}\text{N})^{16}\text{B}$ reaction study [10], (b) the present work and those predicted below 3 MeV predicted by $(0+1)\hbar\omega$ shell model calculations: (c) Ref. [29] (for which only the first four levels were tabulated), (d) Ref. [28] and (e) the present work. The energy is given with respect to the neutron decay threshold. The shaded bands correspond to the uncertainties in the measurements. In the case of the shell model predictions, the energy of the ground state has been taken as the single-neutron separation energy of 164 keV predicted by Ref. [28].

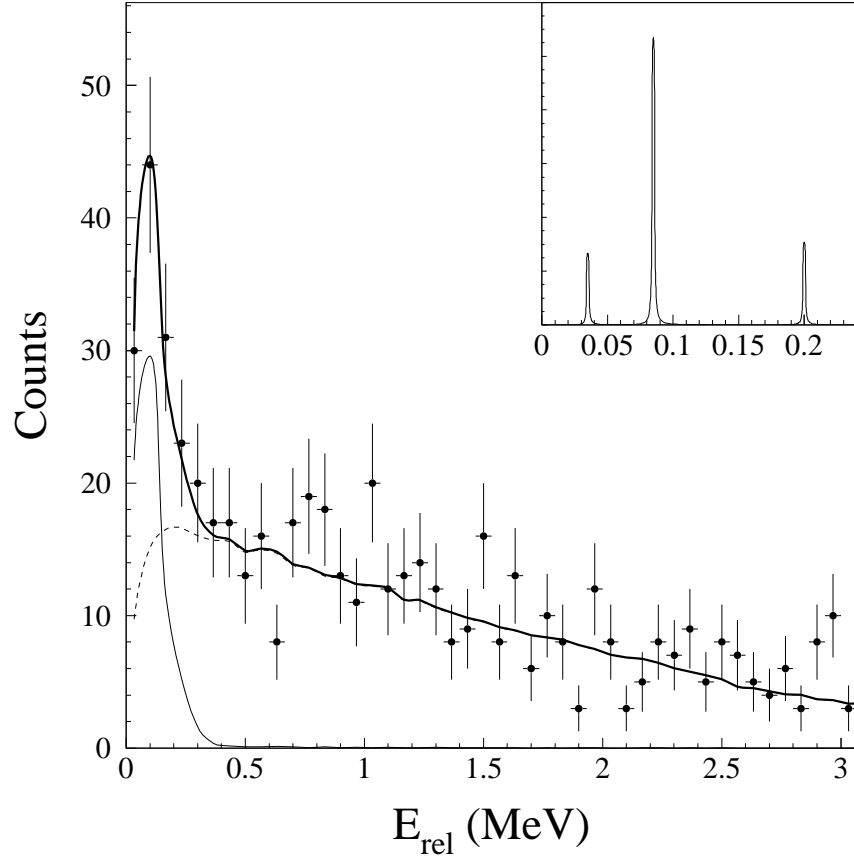


FIG. 5: The $^{15}\text{B}-n$ relative energy spectrum compared to a simulation in which the separation between the 0_1^- , 3_1^- and 2_1^- levels has been reduced ($E_r=35$, 85 and 200 keV) compared to the shell model calculations listed in Table I. The relative strengths correspond to those predicted (see inset).